

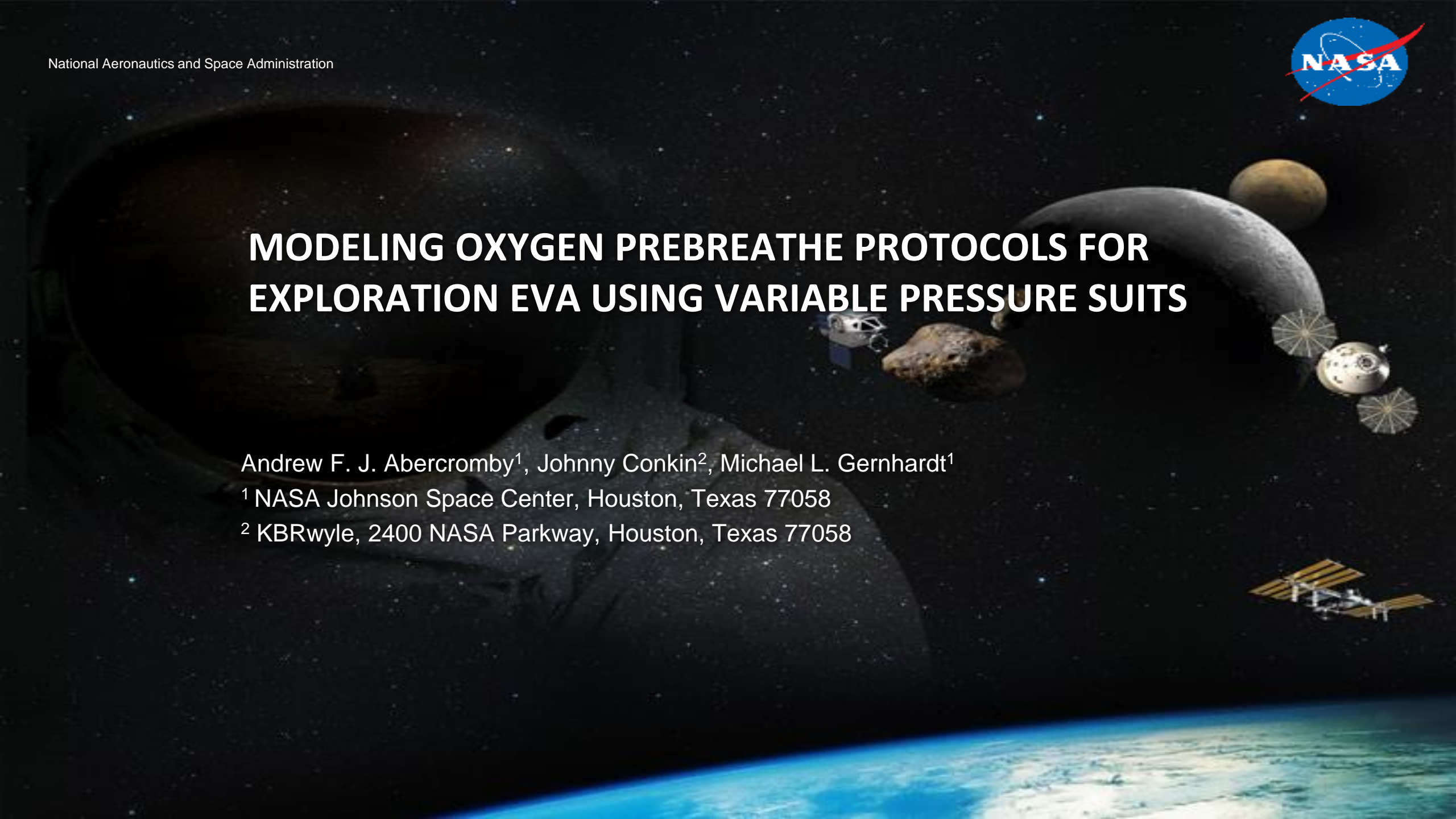


MODELING OXYGEN PREBREATHE PROTOCOLS FOR EXPLORATION EVA USING VARIABLE PRESSURE SUITS

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Disclosure Information
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I have no financial relationships to disclose.

I will not discuss off-label use and/or investigational use in my presentation.

Disclaimer:

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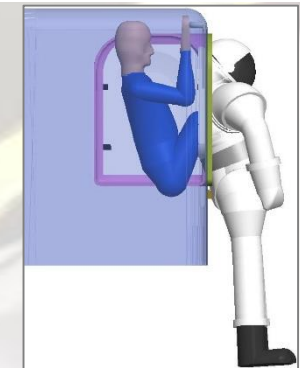
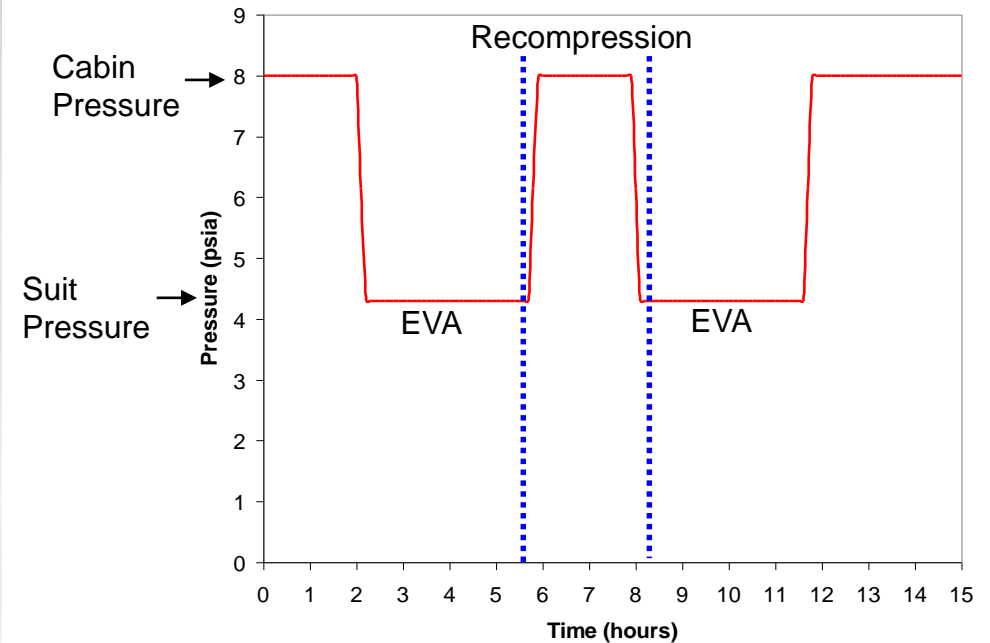
- Exploration missions are expected to use variable pressure spacesuits as well as a spacecraft “exploration atmosphere” of 56.5 kPa (8.2 psia), 34% O₂
 - Both provide the possibility of reducing the oxygen prebreathe times necessary to reduce decompression sickness (DCS) risk.
- Previous modeling work predicted 8.4% DCS risk for an EVA beginning at the exploration atmosphere, followed by 15 minutes of in-suit O₂ prebreathe, and 6 hours of EVA at 29.6 kPa (4.3 psia).
- In this study we model notional prebreathe protocols for a variable pressure suit where the exploration atmosphere is unavailable.



Background: Intermittent Recompression



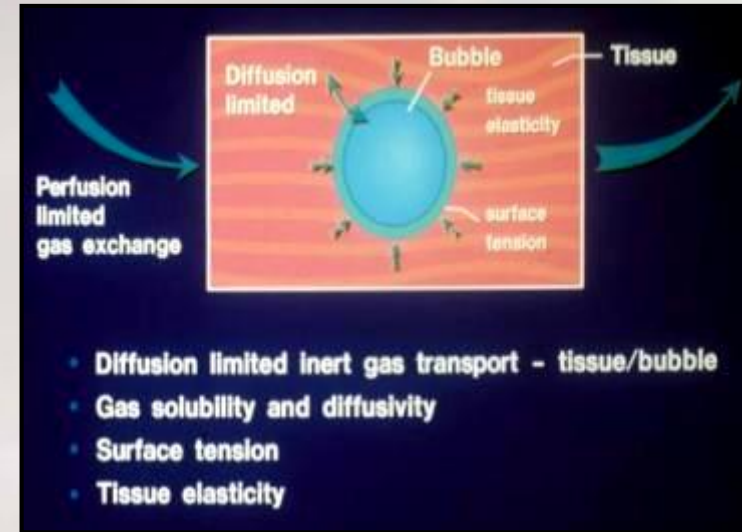
- Intermittent Recompressions (IR) during saturation decompression previously proposed as a method for decreasing decompression stress and time (*Gernhardt, 1988*)
 - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues
- Previous modeling work and empirical human and animal data indicate that IR between EVA suit pressure (≤ 4.3 psia, 100% O₂) and cabin pressure (8 psia, 32% O₂) may reduce decompression stress
- IR has been shown to decrease decompression stress in humans and animals (Pilmanis et al. 2002, Møllerlækken et al. 2007)



Methods: Tissue Bubble Dynamics Model



- Decompression stress index based on tissue bubble growth dynamics (*Gernhardt, 1991*)
- *Diving: n=6437 laboratory (430 DCS cases)*
 - *Logistic Regression Analysis: $p < 0.01$*
 - *Hosmer-Lemeshow Goodness of Fit = 0.77*
- *Altitude: n=345 (57 DCS, 143 VGE)*
 - *Logistic Regression Analysis (DCS): $p < 0.01$*
 - *Logistic Regression Analysis (VGE): $p < 0.01$*
 - *Hosmer-Lemeshow Goodness of Fit (DCS): $p = 0.35$*
 - *Hosmer-Lemeshow Goodness of Fit (VGE): $p = 0.55$*



$$\frac{dR}{dt} = \frac{\frac{\alpha D}{h(r,t)} \left[P_a - vt + \frac{2\gamma}{r} + \frac{4}{3} \pi r^3 M - P_{Total} - P_{metabolic} \right] + \frac{rv}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3} \pi r^3 M}$$

t = Time (sec)
 α = Gas Solubility ((mL gas)/(mL tissue))
 D = Diffusion Coefficient (cm²/sec)
 $h(r,t)$ = Bubble Film Thickness (cm)
 P_a = Initial Ambient Pressure (dyne/cm²)
 v = Ascent/Descent Rate (dyne/cm²·cm³)
 γ = Surface Tension (dyne/cm)
 M = Tissue Modulus of Deformability (dyne/cm²·cm³)
 P_{Total} = Total Inert Gas Tissue Tension (dyne/cm²)
 $P_{metabolic}$ = Total Metabolic Gas Tissue Tension

- **Logistic Regression**

- Logistic regression quantitatively relates the TBDM Bubble Growth Index (BGI) to a % DCS risk based on existing altitude DCS data
- Performed using DCS and VGE data from NASA Bends Tests 1-11b
 - n=668, 84 DCS cases
 - 12.5% DCS, 33.8% VGE
- Prebreathe staged decompressions and includes data points at 10.2, 6.5, 6.0, and 4.3 psi
- BGI provided significant prediction of DCS and VGE data ($p < 0.01$)
- Hosmer-Lemeshow Goodness-of-Fit statistic: $p=0.26$ for DCS, indicating a good fit of the data
 - For Hosmer-Lemeshow statistic, $p > 0.05$ rejects the hypothesis that there is a significant difference between the model predictions and the observed data

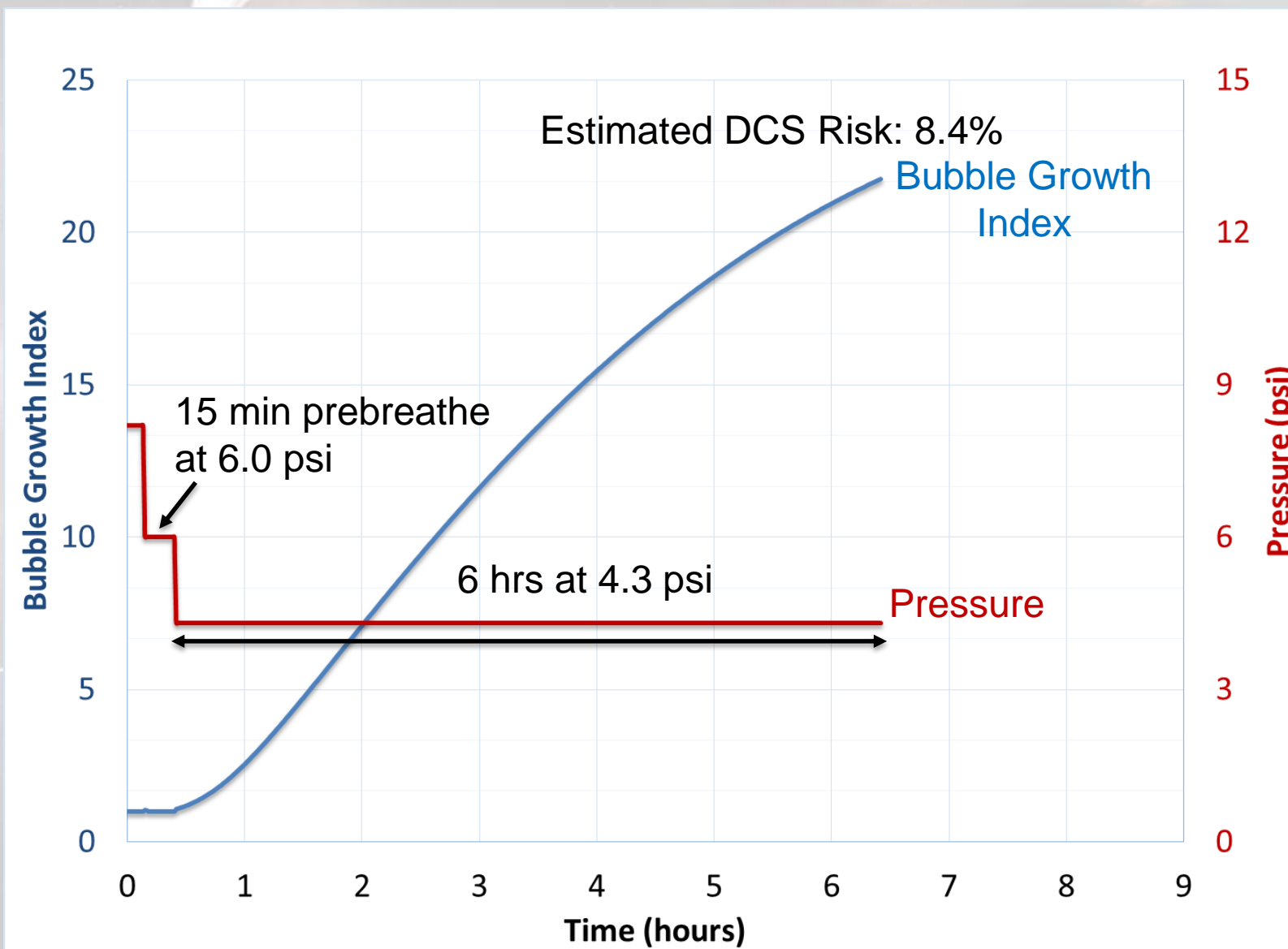
- Four EVA Scenarios were compared:
 - Baseline of comparison (“Case 1”) was a 15-min Exploration Atmosphere prebreathe followed by 6 hours EVA at 95% O₂ (*Abercromby et al, 2015*)
 - Comparison conditions, (Cases 2 and 3) began from saturation at 14.7 psia, 21% O₂, followed by 95% O₂ breathing at suit pressures ranging from 8.2 to 4.3 psia for up to 6 hours.
 - Prebreathe duration for Cases 2 and 3 were iterated to achieve model-predicted DCS Risk equivalent to Case 1 (8.4%)
 - The final comparison condition (Case 4) was identical to Case 3 but also included 2 x 15 minute intermittent recompressions back to 8.2 psi

	Case 1	Case 2	Case 3	Case 4
Starting Atmosphere	8.2 psi, 34% O ₂ , 66% N ₂	14.7 psi, 21% O ₂ , 79% N ₂		
Prebreathe	15 mins at 6.0 psi	120 mins at 14.7 psi		
EVA Description	6 hrs at 4.3 psi	4 hrs at 8.2 psi 2 hrs at 4.3 psi	3 hrs at 8.2 psi 2 hrs at 6.0 psi 1 hr at 4.3 psi	3 hrs at 8.2 psi 2 hrs at 6.0 psi with 2 x 15 min IR to 8.2 psi 1 hr at 4.3 psi

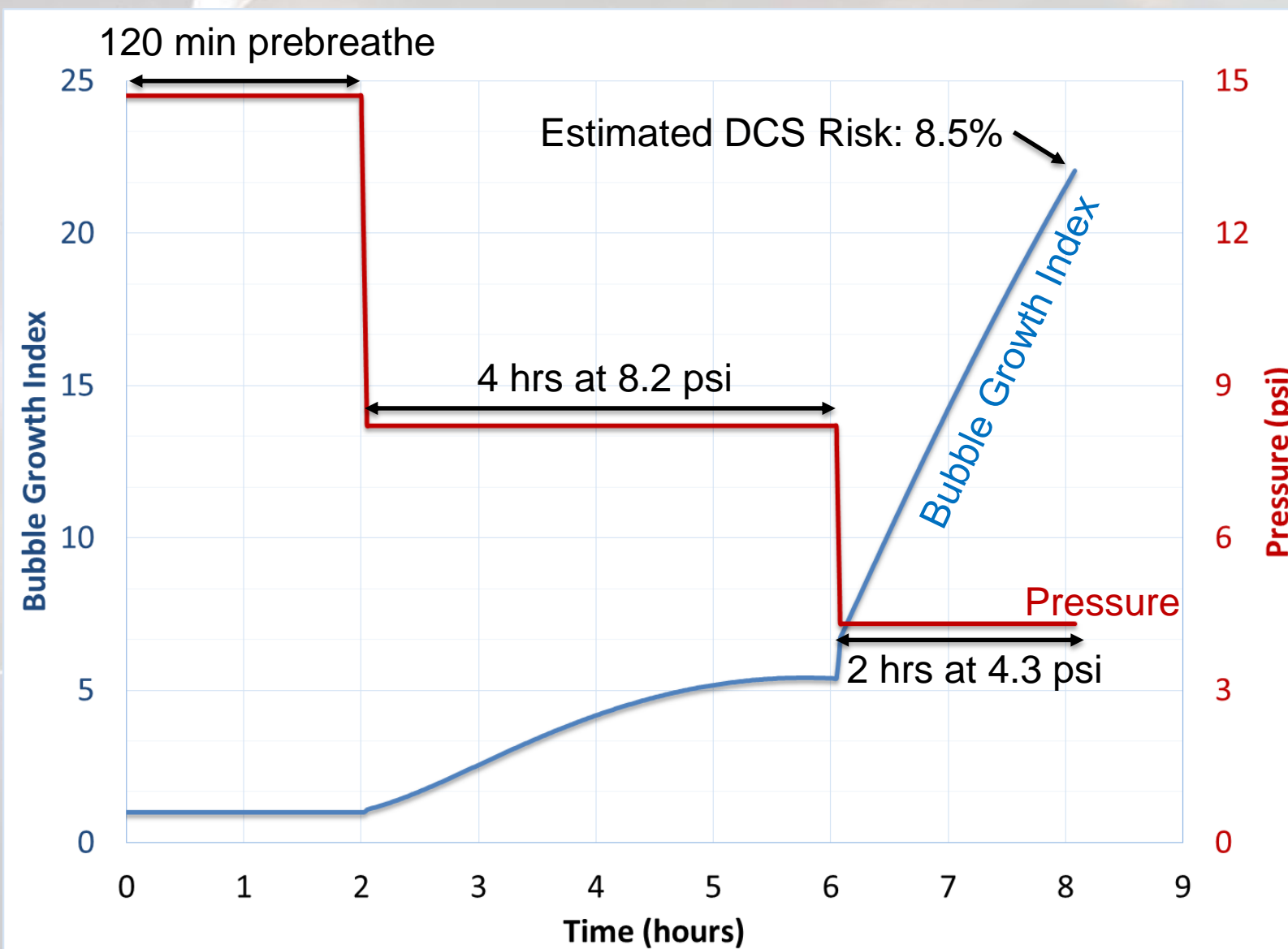
- **Model Predictions:**

- 4 hours at 8.2 psi followed by 2 hours at 4.3 psi requires a 2 hour prebreathe to limit DCS risk to 8.5%.
- Same 2 hour prebreathe would alternatively allow for 3 hours at 8.2 psi, 2 hours at 6.0 psi, and 1 hour at 4.3 psi with 8.4% predicted DCS risk.
- The predicted DCS risk for the latter scenario reduces to 7.9% (0.5% reduction) when two 15-minute recompressions to 8.2 psi are added during the 2 hours at 6.0 psi.

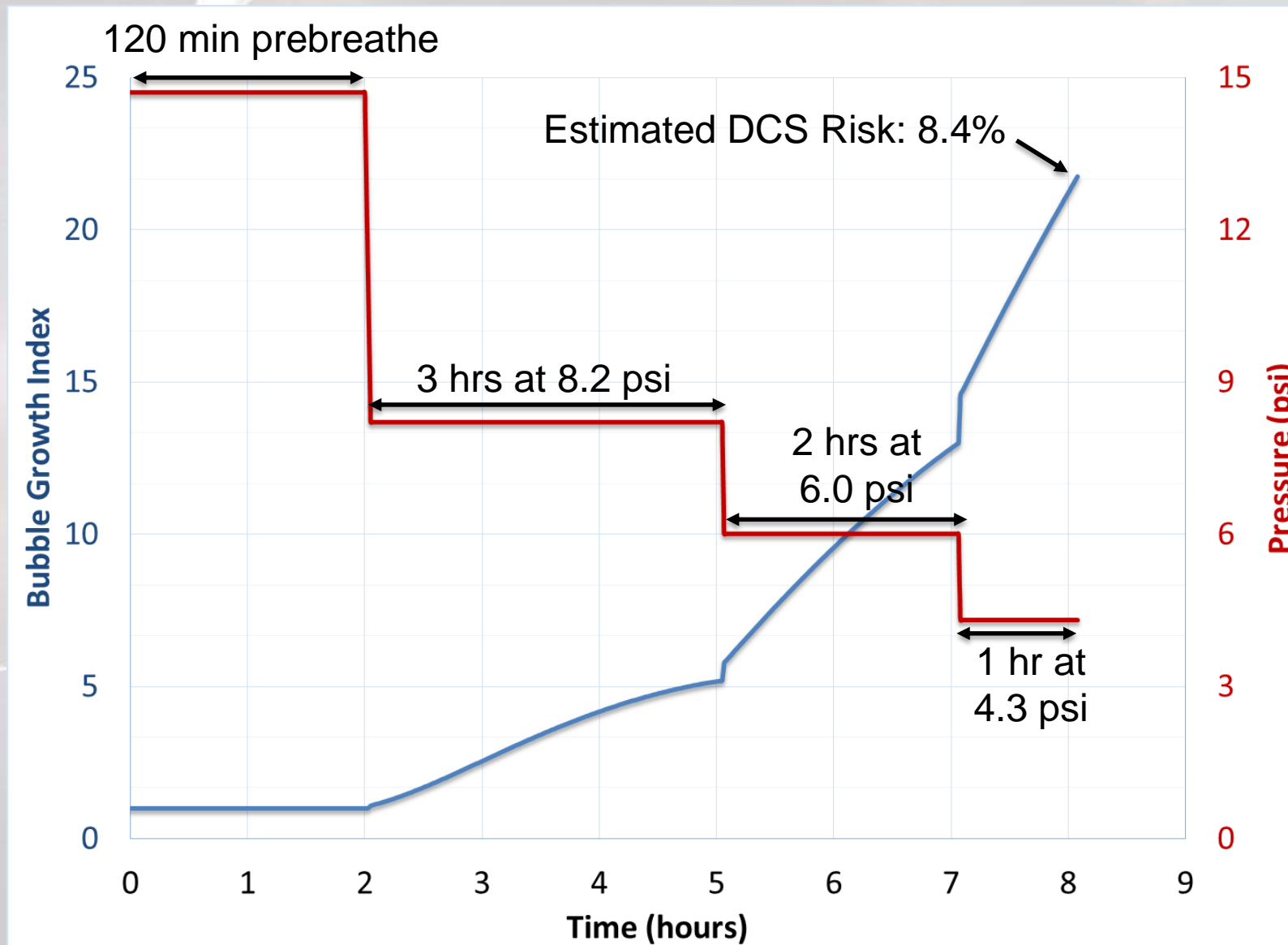
Case 1: 6 hour EVA at 4.3 psi, Starting at 8.2 psi / 34% O2



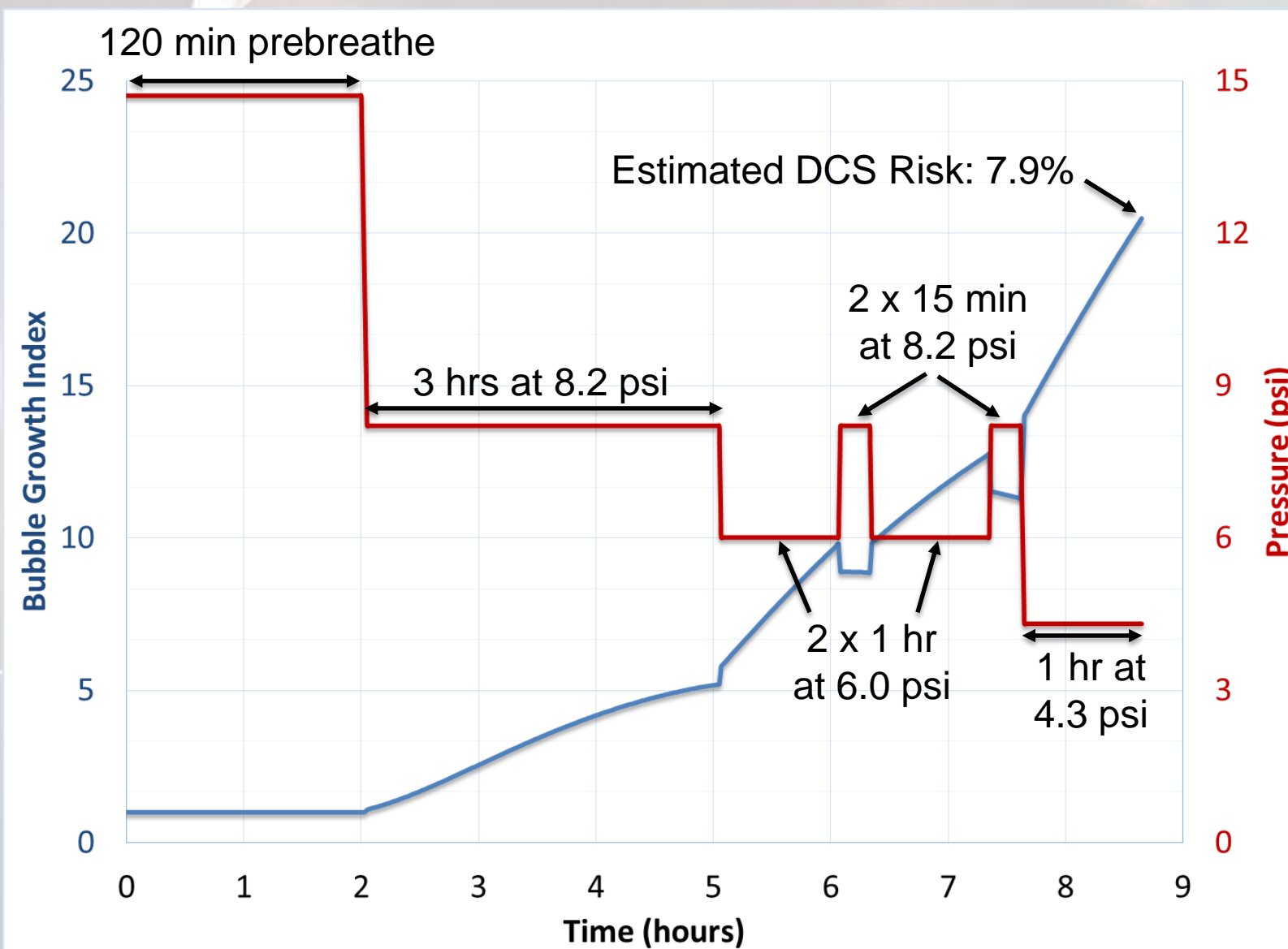
Case 2: 4 hours at 8.2 psi, 2 hours at 4.3 psi



Case 3: 3 hours at 8.2 psi, 2 hours at 6.0 psi, 1 hour at 4.3 psi



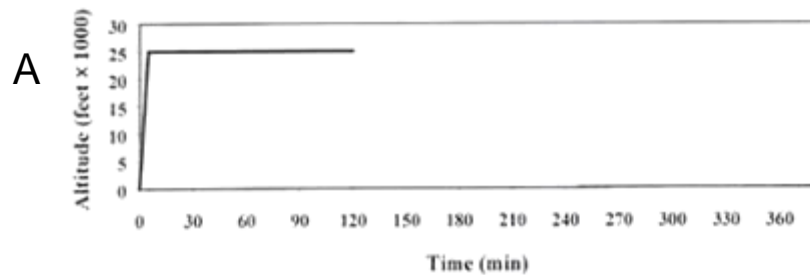
Case 4: 3 hours at 8.2 psi, 2 hours at 6.0 psi, 1 hour at 4.3 psi plus 2 x 15 min Intermittent Recompressions



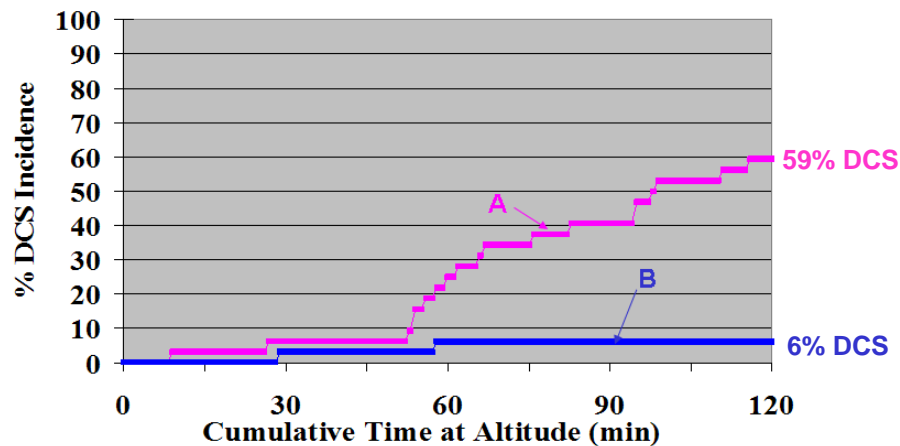
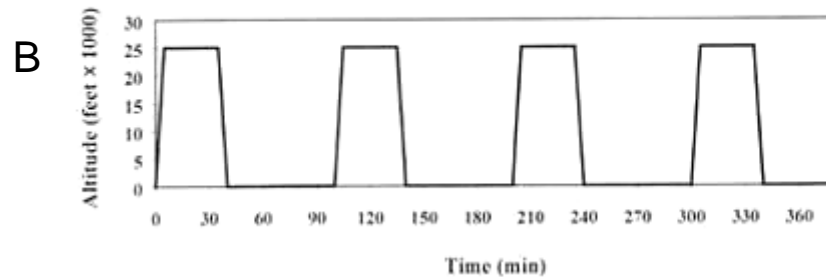
Intermittent Recompression



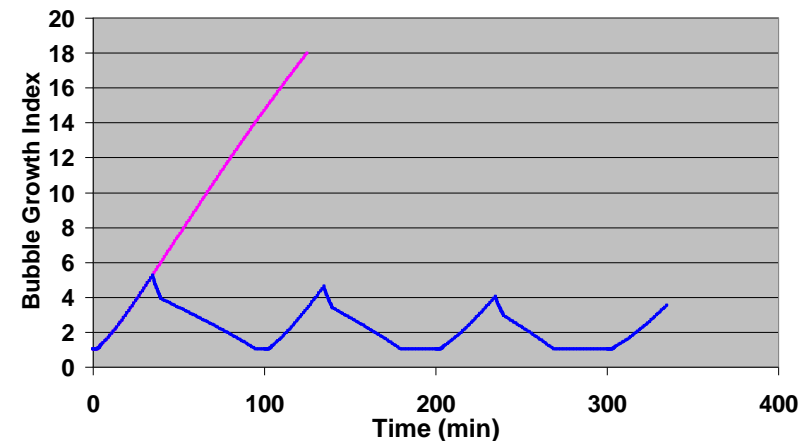
A. One 2-h exposure, no preoxygenation



C. Four 30-min exposures, 1-h ground-level interval on air, no preoxygenation



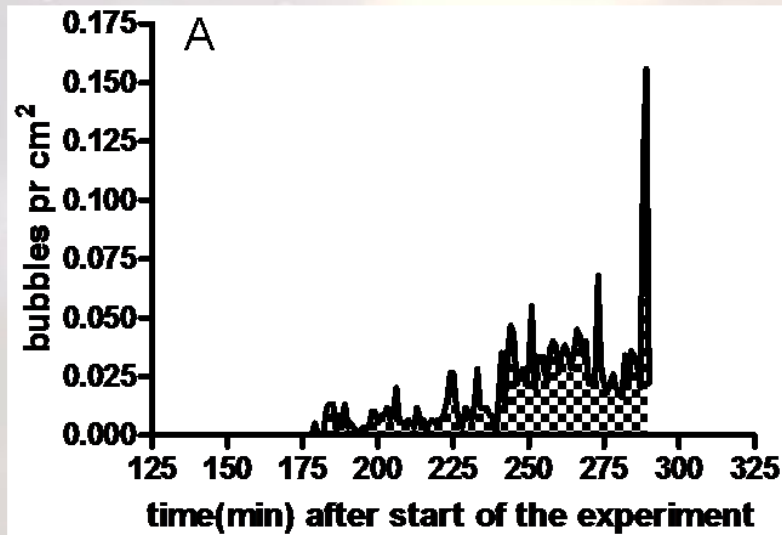
DCS Incidence



TBDM Predictions

Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. *Aviat Space Environ Med*; 73: 525-531, 2002.

Without Intermittent Recompression



With Intermittent Recompression

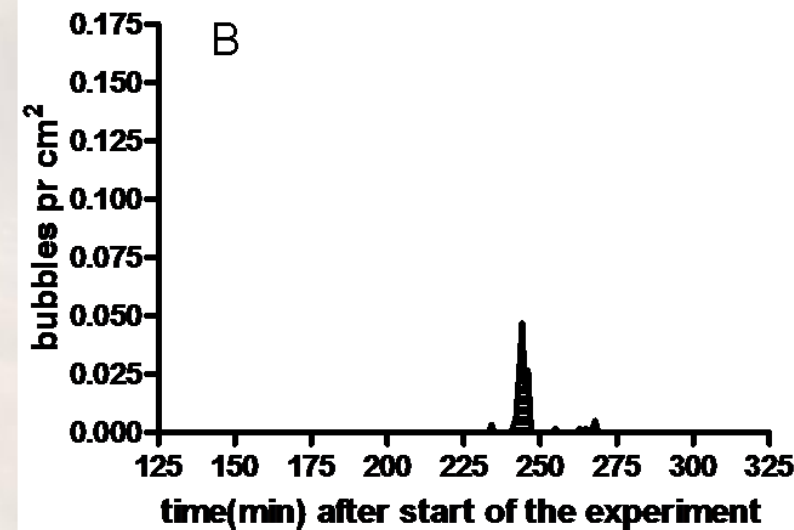
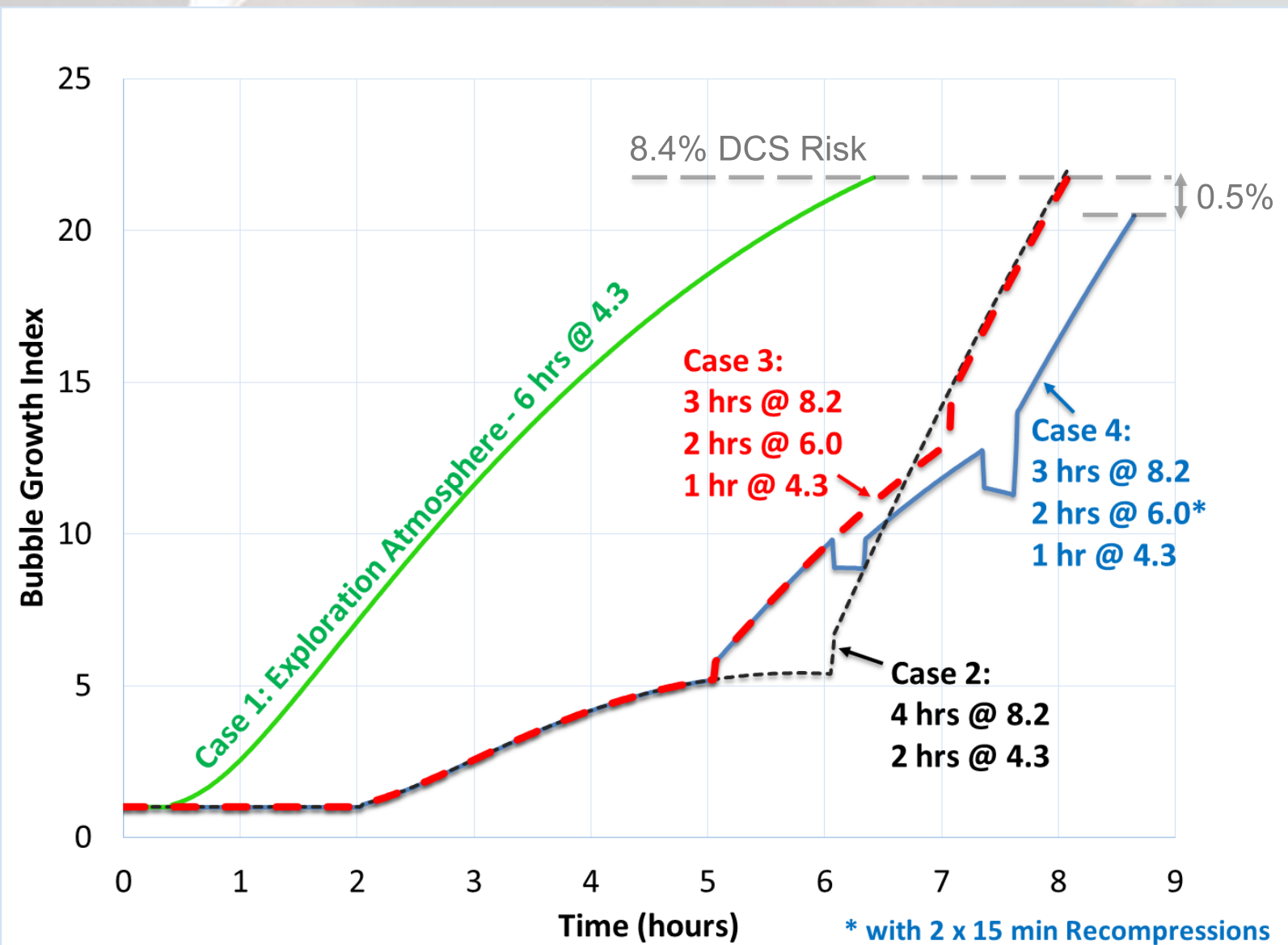


Fig. 10. Two groups of six pigs were compressed to 121 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression (control group). The control profile was a USN profile for this exposure, where the stop times were reduced by 50% as pilot studies showed that the standard USN profile produced very few bubbles. The average number of venous gas bubbles measured in the pulmonary artery during the decompression is shown for the control group (A) and the experimental group (B). The results indicate significantly fewer bubbles in the experimental group than in the control group ($p < .0001$). From Møllerlækken et al. (5) by permission.

Comparison of BGI Profiles for All Cases



1. **Prebreathe benefits of variable pressure suits are limited** if crewmembers are initially saturated at 101.3 kPa (14.7 psia), 21% O₂
2. Any potential benefits may be outweighed by **increased fatigue and injury risk** associated with working in high pressure suits
 - Additional work is warranted to understand human health and performance impacts of high-frequency EVA at higher suit pressures (e.g. 24hrs/person/week)
3. **Minimal benefit of Intermittent Recompression (IR) is predicted** for these scenarios because significant gas phase growth has already occurred before IR is available
4. **Variable pressure EVA suits, in combination with reduced ppN₂ atmospheres, offer advantages for operational efficiency as well as crew health and safety** due to decreased decompression stress and availability of expedited repressurization in the event of DCS
5. Development of exploration prebreathe protocols will begin with definition of acceptable risk, followed by development of protocols based on models such as ours, and, ultimately, **validation of protocols through ground trials** before operational implementation.